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2014 JINST 9 C01053

(http://iopscience.iop.org/1748-0221/9/01/C01053)

Published by IOP Publishing for Sissa Medialab

Received: *December 10, 2013*
Accepted: *December 26, 2013*
Published: *January 29, 2014*

13th Topical Seminar on Innovative Particle and Radiation Detectors
7–10 October 2013
Siena, Italy

# Studies on the upgrade of the muon system in the forward region of the CMS experiment at LHC with GEMs

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doi:10.1088/1748-0221/9/01/C01053

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ABSTRACT: The LHC data-taking will resume in 2015 with energy of 13–14 TeV and luminosity of $2 \div 5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. At those energies, a considerable fraction of the particles produced propagate in the high pseudo-rapidity regions. The proposal for the upgrade of the CMS muon forward system involves Gas Electron Multiplier (GEM) chambers to be installed during the second LHC Long Shutdown (LS2) covering the pseudorapidity range $1.5 < |\eta| < 2.2$. This detector is able to handle the extreme particle rates expected in this region when the LHC will be running at higher luminosity. The GEM is an excellent choice, as its high spatial resolution (order of 100 $\mu$m) allows to combine tracking and triggering capabilities, which will improve the CMS muon High Level Trigger, the muon identification and the track reconstruction. Intense R&D has been going on since 2009 and it has lead to the development of several GEM prototypes and associated detector electronics. These GEM prototypes have been subjected to extensive tests in the laboratory and in test beams at the CERN Super Proton Synchrotron (SPS). This contribution will review the status of the CMS upgrade project with GEMs, discussing also the trigger performance.

KEYWORDS: Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Muon spectrometers

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## 1 Introduction

The CMS muon system [1] is designed to provide robust, redundant and efficient identification and reconstruction of the muons traversing the system identification, in addition to trigger capabilities. For the initial phase of CMS, three types of gaseous detection technologies have been chosen, according to the different background rates and magnetic field the detectors have to withstand: Drift Tubes (DTs) and Cathode Strip Chambers (CSCs) in the barrel and endcaps respectively, Resistive Plate Chambers (RPCs) in both the barrel and the endcaps.

Figure 1 shows a quadrant of the CMS detector as it will appear after the ongoing first LHC Long Shutdown (LS1): for $\eta > 1.6$ the CMS muon identification will rely entirely on the CSC system, which has been showing a good performance but whose trigger efficiency could degrade as LHC luminosity will increase in the future years. The presence of an additional muon detector in that region could improve the muon reconstruction and trigger, by measuring the muon bending angle between CSCs and this new detector.

## 2 The CMS-GEM project

In view of the next two long shutdown periods the CMS GEM Collaboration proposed Gas Electron Multipliers (GEMs) [2] to upgrade the muon system, instrumenting the non-redundant CMS high-$\eta$ region [3] with detectors that could be suitable for operation at the LHC and its future upgrades.

The GEM detector is a thin metal-coated polymer foil perforated with a high density of holes, each hole acting as multiplication region. Single GEM foils can operate up to gains of several thousands and can be used in cascade. Triple-GEM detectors, made with three GEM foils in cascade, ensure high gains and safe operation at low voltage.

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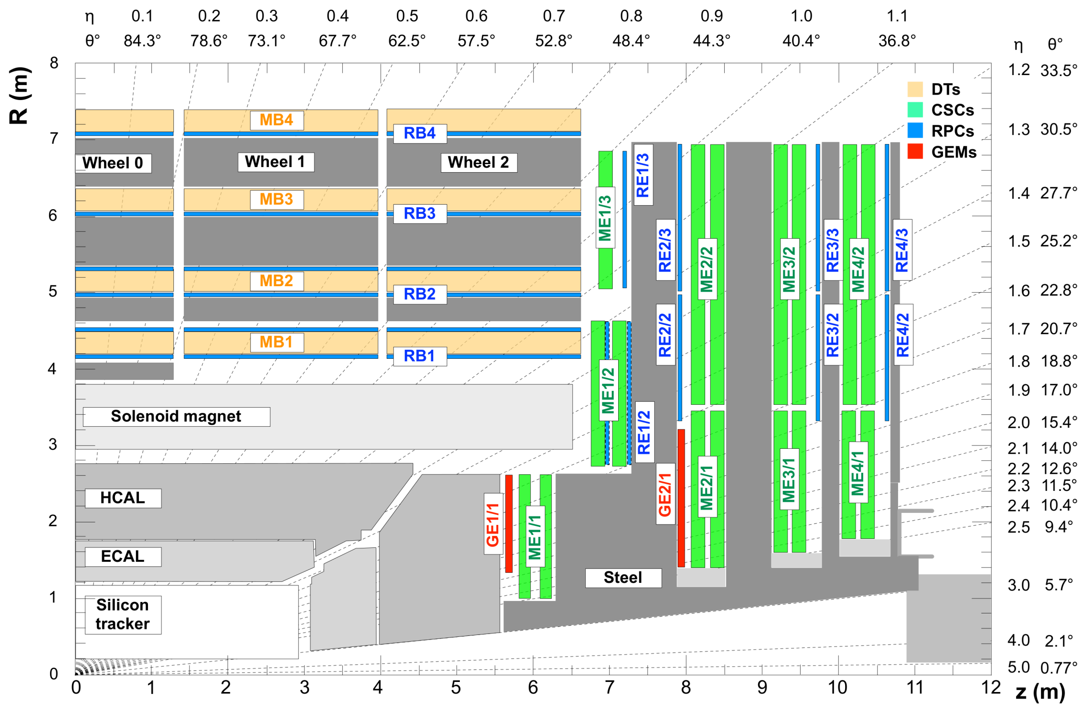


**Figure 1**. Quadrant of the CMS detector showing the present muon system including RPCs, DTs and CSCs. The proposed locations for the GEM detectors in the inner endcap stations are indicated by the red boxes.

GEM based detectors feature high spatial resolution ($\sim 100\,\mu$m) and a time resolution of $\sim 4$ ns and are able to withstand particle rates up to 10 MHz/cm$^2$ with detection efficiencies above 98%[4]. These are required to improve muon momentum resolution for high $p_T$ muons and to provide overall highly efficient muon trigger and tracking capabilities. To provide an independent local pattern recognition two layers ("Super-Chamber") of Triple-GEM detectors will be installed. Thus each Super-Chamber will provide two impact points for each muon track.

In the presently proposed schedule, the inner endcap stations (called GE1/1) would be equipped with the GEM Super-Chambers during the second LHC Long Shutdown in 2017–2018, while the installation in the second endcap stations (labeled GE2/1) would be done during the third LHC Long Shutdown scheduled beyond 2020. The foreseen layout is also shown in figure 1.

## 3 Impact on trigger

The installation of the GEMs is aimed at maintain the existing forward muon trigger coverage of $|\eta| < 2.4$ reducing the trigger rate in the region which currently suffering from the highest background rates and a non-uniform magnetic field. Trigger rate reduction is possible with the improved momentum resolution deriving from precision measurements of the bending angle (see figure 2, left) performed measuring the lever arm between the existing CSC chambers in stations ME1/1 and the triple GEM detectors in new GE1/1 station (see figure 2, right) [5].

GEM hits are matched with the muon candidates from the CSC system for a specific bunch crossing and from the position in the two chambers it is possible to calculate the bending. The

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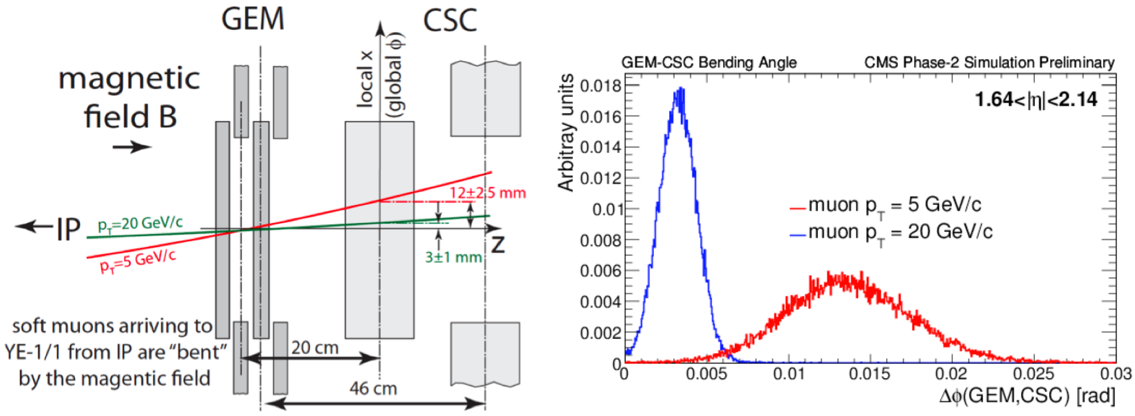


**Figure 2**. Left: visualization of the GE1/1 GEM Super-Chambers and ME1/1 CSCs. The distances between the pairs of GEM and CSC chambers, which act as lever arms in the muon momentum measurement, are fixed to 20 cm and 46 cm. The muon bending angle for a 5 GeV and a 20 GeV muon track is shown. Right: comparison of GEM-CSC bending angle distributions measured between GE1/1 and ME1/1 stations for muons with low $p_T$ (5 GeV) and high $p_T$ (20 GeV) for a lever arm equal to 46 cm.

plot in figure 2 (right) shows the comparison of GEM-CSC bending angle distribution for muons with $p_T$ equal to 5 GeV and 20 GeV, for a lever arm equal to 46 cm. It is evident that the bending angle measurement could be used in the trigger to discriminate high-momentum muons from low-momentum muons.

The trigger rate reduction in the region $1.6 < |\eta| < 2.1$ covered by the new station GE1/1 is shown in figure 3. The trigger rate reduction is primarily due to better discrimination of high transverse momentum muon candidates obtained by measuring the bending angle with pairs of GEM and CSC chambers. Results are compared with the standard CMS configuration used in 2012 (red line) modified to account for the improved ME1/1 detector electronics to be installed in LS1. In the two simplified scenarios shown, the tracks satisfy the requirement of having reconstructed trigger hits in at least two (figure 3, left) or three (figure 3, right) stations out of four possible. The plots demonstrate the increased dynamic range available for optimizing the muon trigger due to the addition of the bending angle.

## 4 Impact on physics

Several benchmark analyses have been studied to understand the impact of the CMS muon forward system upgrade on the physics performance. Benchmark channels critical for both bosonic and fermionic Higgs couplings include the golden decay channel of a SM higgs boson $\mathrm{H} \to \mathrm{ZZ} \to 4\mu$, that is a key channel for measuring bosonic couplings, and the decay of a SM Higgs to 2 tau $\mathrm{H} \to 2\tau$ with one $\tau$ decaying to muon and neutrinos, key for measuring fermionic couplings. The trigger rate reduction offers the possibility of lowering the muon momentum thresholds with an important impact on these channels.

The improvement achievable by extending the detector $\eta$ coverage is shown in figure 4 (left). In the $\mathrm{H} \to \mathrm{ZZ} \to 4\mu$ decay the muons are produced in the $p_T$ range $\sim 10 \div 50$ GeV. The fraction of muons in GE1/1 region is $\sim 20\%$ and $\sim 39\%$ of the events are outside of the present $\eta$ acceptance.

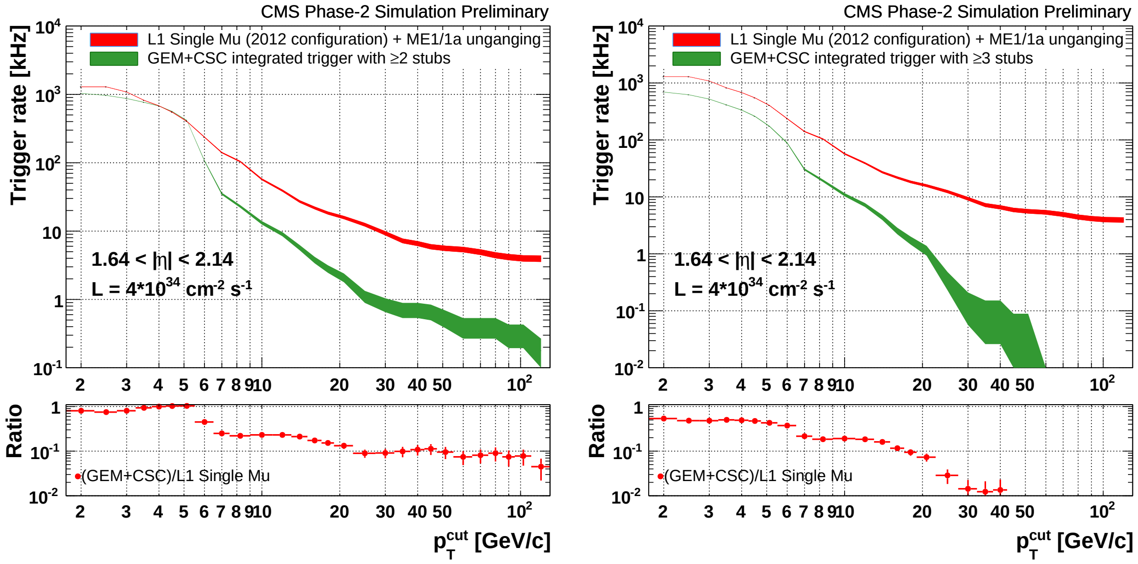


**Figure 3**. Left: comparison of the trigger rate for the Global Muon Trigger in the 2012 configuration with reconstructed trigger hits (stubs) in at least 2 CSC stations and the configuration with at least 2 stubs in the CSCs and a GEM signal. The bottom panel shows the ratio of the two configurations. Right: comparison of the trigger rate for the Global Muon Trigger in the 2012 configuration with reconstructed trigger hits (stubs) in at least 3 CSC stations and the configuration with at least 3 stubs in the CSCs and a GEM signal. The bottom panel shows the ratio of the two configurations.

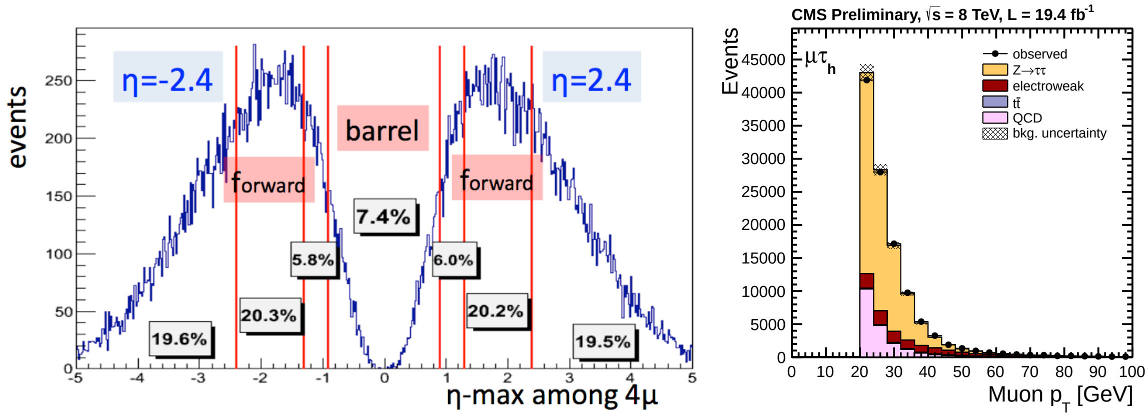


**Figure 4**. Left: $H \to ZZ \to 4\mu$ channel. Pseudorapidity distribution of the most forward muon. Right: $H \to 2\tau$ with one tau decaying to muon and neutrinos channel. Distribution of the muon transverse momentum for the events selected by the $H \to 2\tau$ official analysis [6].

Reconstruction of all four these muons is needed, but the efficiency of both trigger and offline selection depends on the local trigger efficiency, on the detector acceptance ($\eta$ coverage) and on the applied $p_T$ thresholds. An increase in $\eta$ coverage and a lower $p_T$ selection cut for single $\mu$ in the forward region would also improve the efficiency for $H \to 4\mu$ event selection.

In the $H \to 2\tau$ channel, the muons from tau-decay have a quite soft $p_T$ distribution with an average $p_T \sim 15\,\mathrm{GeV}$ [6]. The fraction of muons in GE1/1 region is $\sim 14\%$ and $\sim 19\%$ of the

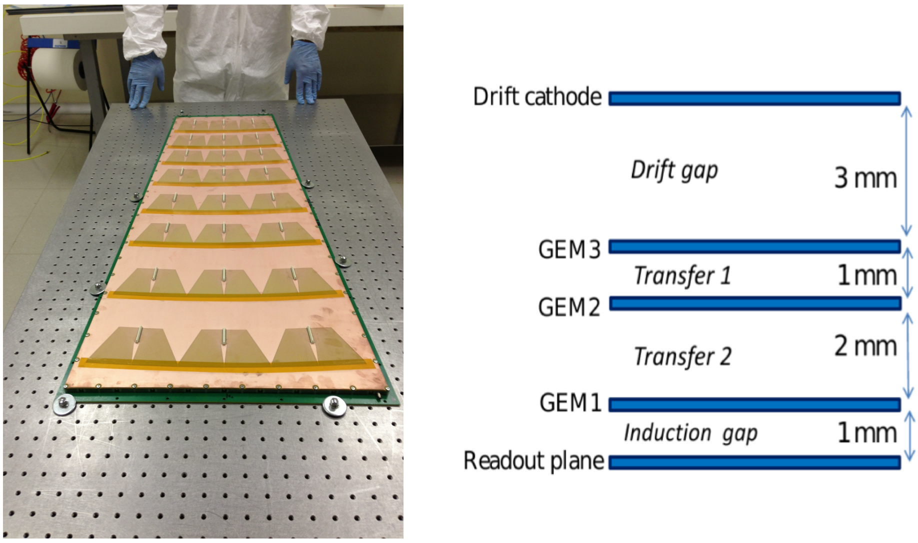


**Figure 5**. Left: the latest version of the GE1/1 prototype as built in 2013 (without cover box) sectorized with eight $\eta$ partitions, each composed of 3 sectors. Right: cross section of the proposed triple-GEM detectors showing the thickness of the different gaps.

events are outside of the present $\eta$ acceptance. This channel requires low muon trigger thresholds. The current kinematic requirement on the muon transverse momentum is $p_T > 20\,\text{GeV}$ (figure 4, right). An increase of $\sim 40\%$ in accepted events would be observed lowering the $p_T$ threshold by 10 GeV in the GEM instrumented area.

## 5 Detector design description

Since 2009, the CMS GEM Collaboration designed and built several types of small and large Triple-GEM prototypes. These prototypes were tested using 150 GeV muon/pion beams at the CERN Super Proton Synchrotron (SPS). After successful tests with small size chambers [3], the collaboration has designed, built and instrumented large-area chambers identical to the ones proposed to be used for the upgrade.

These trapezoidal chambers have a active area of $990 \times (220 \div 455)\,\text{mm}^2$, are sectorized in $\eta$ partitions and provide radial readout strips with the strips pointing to the LHC beam pipe (see figure 5, left). In the present design, the strip pitch varies from 0.6 mm (lower side) to 1.2 mm (upper side) with eight $\eta$ partitions. The thicknesses of the gaps between the GEM foils in the Triple-GEM chamber (figure 5, right) are: 3/1/2/1 mm (drift/transfer-1/transfer-2/induction regions). The gas mixture is $Ar/CO_2/CF_4$ 45/15/40. GEM foil production was performed with the so-called “Single-Mask” technique, which proved to overcome known limitations with previous standard techniques. The chambers were assembled using the so-called “NS2” (no stretching no spacers) technique (figure 6) that consists of mechanically stretching the GEM foils as part of the assembly procedure without the need to put spacers and without glue; this allows to assemble and disassemble the chamber as many times as needed (more details in ref. [7, 8]). As illustrated in figure 6, outside the active area, the edges of the GEM foils contain a pattern of holes which is used to attach each of the 3 foils with nylon pins to an inner frame structure; this inner frame defines the gap sizes



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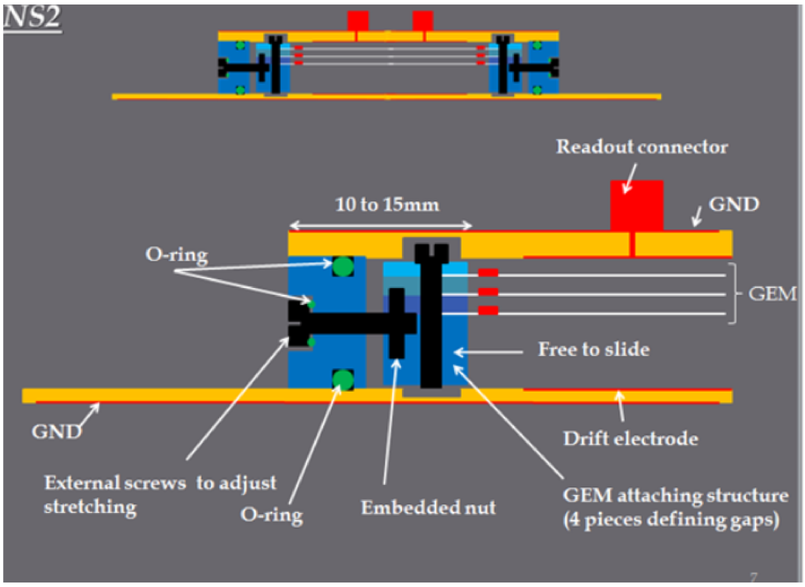


**Figure 6**. Transverse section of a Triple-GEM chamber assembled with the so-called "NS2" (no stretching no spacers) technique.

and is placed inside an outer frame. By tightening the screws passing through the outer frame and fitting into nuts inside the inner frame, the 3 foils are mechanically stretched. The outer frame is designed to withstand the tension of the foils. With this technique a Triple-GEM chamber can be assembled in a few hours time, in contrast to the old thermal stretching and gluing method which took several days.

## 6 Test beam results of large prototypes

Some large scale GEM chamber prototypes were tested in 2012 at the SPS H2 beam line at CERN with 150 GeV muon/pion beams [9, 10]. A small-area ($10 \times 10\,\mathrm{cm}^2$) hodoscope made of GEM chambers was used to predict the hits position in the test chambers.

Since each of the eight $\eta$ partitions is sectorized along the $\Phi$-coordinate into 3 readout sectors with 128 strips each, 3072 channels are needed for the whole chamber. During the test beam, the readout was performed using digital TURBO/VFAT2-based [11] front-end electronics. The power supply was performed using a ceramic high voltage divider.

The efficiency obtained with an HV scan of one sector is shown in figure 7 (left). An efficiency of 98% was obtained when the detector was operated with an HV that corresponds to a gain of $\approx 7000$. Figure 7 (right) shows the residual between the impact position of the track reconstructed by the hodoscope and then extrapolated to the test chamber and the hit position measured by the test chamber for an $\eta$ partition where the strip pitch is around 900 $\mu$m. The measured spatial resolution of 268 $\mu$m is in agreement with the theoretical expected value of 260 $\mu$m for this strip pitch. A time resolution of 4 ns was obtained [4].

It is very important to check carefully the uniformity of response of the chamber to be sure that it is not affected by the large size of the chamber and the varying pitch along the strips. An

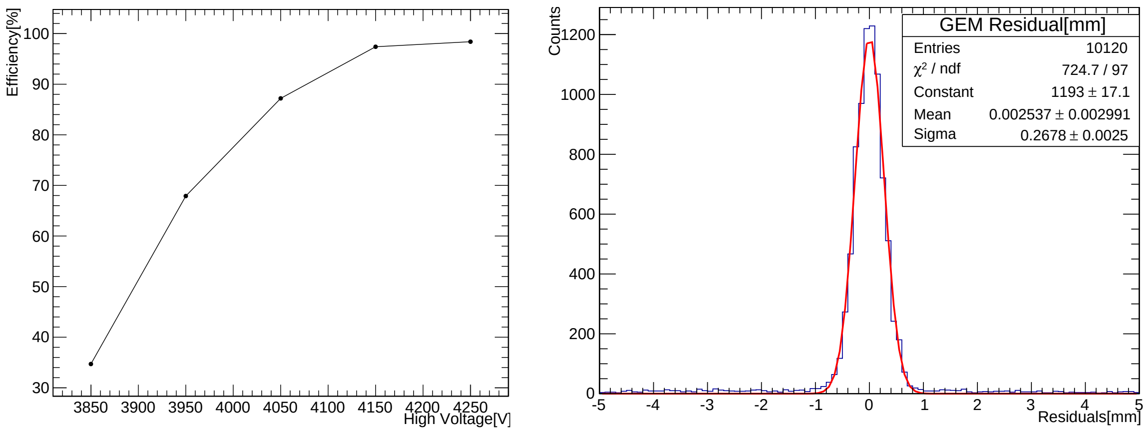


**Figure 7**. Left: detection efficiency as a function of the HV divider current. Right: residual between the impact position measured by the CMS GEM chamber of the one extrapolated by the hodoscope.

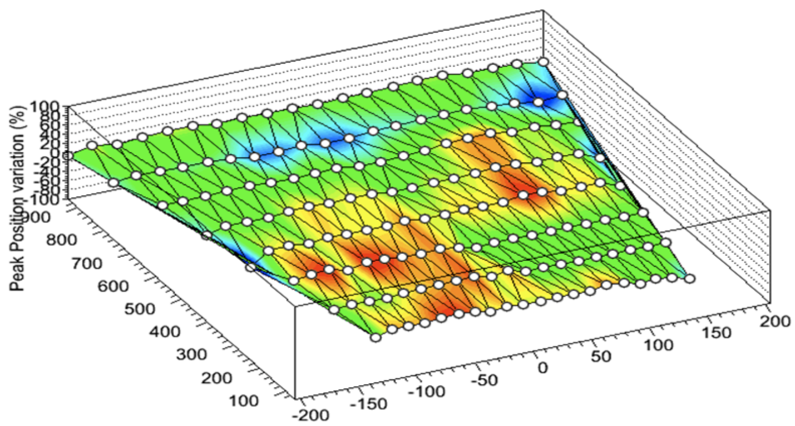


**Figure 8**. Results from uniformity studies with X-ray beams. The collected cluster charge across the full chamber active area. Each point represents the mean value of a Gaussian fit to the charge distribution collected by 30 adjacent strips.

uniformity test, similar to the ones foreseen to be part of the quality control check during final production, was conducted by scanning the full chamber with a Cu-based X-ray beam at the Gamma Irradiation Facility (GIF) at CERN. The complete setup is detailed in [8]. Figure 8 gives the gain across the full active area of the test chamber. A variation in the collected charge across the GEM area lower than 15% was measured.

## 7 Summary and outlook

The CMS GEM collaboration has proposed, for the upgrade of the CMS muon forward system, to instrument the pseudorapidity range $1.5 < |\eta| < 2.2$ with GEM chambers during the second and third LHC Long Shutdowns (LS2 and LS3). Many feasibilities and performance studies have been performed with small and large-area Triple-GEM detectors. Experimental results proved that the detector performs well. Good detection efficiency and spatial resolution were successfully proven.

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As a consequence, the CMS collaboration recently approved the installation during the 2016 LHC Year End Technical Stop of a demonstrator system, i.e. three GE1/1 super-chambers, identical to the ones proposed for installation in CMS during the LS2 and covering a 30° sector of one inner endcap station. This will allow to gain operational and integration experience and reduce the GEM commissioning period in the future.

## References


[1] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004.

[2] F. Sauli, *GEM: a new concept for electron amplification in gas detectors*, *Nucl. Instrum. Meth.* **A 386** (1997) 531.

[3] D. Abbaneo et al., *GEM based detector for future upgrade of the CMS forward muon system*, *Nucl. Instrum. Meth.* **A 718** (2013) 383.

[4] G. Bencivenni et al., *Performance of a triple-GEM detector for high rate charged particle triggering*, *Nucl. Instrum. Meth.* **A 494** (2002) 156.

[5] A. Castaneda et al., *Potential impact of a new GEM-based muon detector on CMS triggering*, in Proceedings of the *Meeting of the American Physical Society Division of Particles and Fields*, Santa Cruz U.S.A., 13–17 Aug 2013.

[6] CMS collaboration, *Search for the standard-model Higgs boson decaying to tau pairs in proton-proton collisions at* $\sqrt{s} = 7$ *and* 8 *TeV*, CMS-PAS-HIG-13-004.

[7] M. Tytgat et al., *Status of the triple-GEM project for the upgrade of the CMS muon system*, 2013 *JINST* **8** C12031.

[8] D. Abbaneo et al., *The status of the GEM project for CMS high-*$\eta$ *muon system*, *Nucl. Instrum. Meth.* **A 732** (2013) 203.

[9] D. Abbaneo et al., *Beam test results for new full-scale GEM prototypes for a future upgrade of the CMS high-*$\eta$ *muon system*, *IEEE Nucl. Sci. Symp. Conf. Rec.* (2012) 1172 [arXiv:1211.3939].

[10] O. Bouhali et al., *Development and performance of large scale triple GEM for CMS*, 2013 *JINST* **8** C11017.

[11] P. Aspell et al., *The VFAT production test platform for the TOTEM experiment*, in Proceedings of *Topical Workshop on Electronics for Particle Physics 2008*, Naxos Greece, 15–19 Sep 2008, CERN-2008-008.


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